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Review of low-cost, off-grid, biodegradable in situ autonomous soil moisture sensing systems: Is there a perfect solution?

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ABSTRACT

Soil moisture monitoring is essential for a variety of applications including agriculture, forestry, and environmental monitoring. However, soil moisture sensors may be expensive and require batteries or other energy sources, making them unsuitable for remote or off-grid locations and farmers. Improper e-waste management of short-lived sensing components can reveal the contradictions of solutions aimed at environmental sustainability, which also degrade environmental health. Therefore, the development of low-cost, off-grid, biodegradable in-situ soil moisture sensing system (SMSS) is necessary for these regions. This article provides an overview of the current state-of-the-art in low-cost, off-grid, and biodegradable in-situ soil moisture sensing. It highlights low-cost SMSS components including hardware (microcontrollers and communication modules), software, and off-grid ambient energy sources. It also highlights the current research in biodegradable polymers used for moisture sensing. The challenges in combining low-cost, off-grid, and biodegradable soil moisture sensing are identified as a research gap. Finally, the underlining question of the "perfect" choice of SMSS is explored based on the trade-offs of performance, operational feasibility, and the newly proposed aspect of biodegradability, consequently suggesting context-specific decisions by consciously managing these tradeoffs.

1. Introduction

The agriculture sector is the highest consumer (~85 – 90 %) of freshwater (Sui et al., 2021) and is among the least efficient users. Agricultural water management using scientific methodologies can improve farm water management by reducing economic losses from over-/under-irrigation, excessive pumping costs, nutrient leaching, and greenhouse gas emissions (Abba and Lee, 2019; Neto et al., 2022).

Soil moisture, which is defined as the amount of water in a specific soil depth [m^3 water per m^3 soil] (Dorigo et al., 2011) and is categorized into gravitational, capillary, and hygroscopic forms, plays a critical role in agricultural water management (S.U. et al., 2014). Among the various forms of soil moisture, capillary moisture, which is held in micropores by cohesion and adhesion, is the most significant for agricultural purposes as it facilitates soil-environment interactions (S.U. et al., 2014). Capillary soil moisture, which is essential for comprehending soil-environment interactions, is typically categorized into field water capacity and wilting point. Field water capacity (FWC) refers to the water retained in the soil following the drainage of any excess gravitational water; however, this water may not always be accessible to plants. The wilting point, or permanent wilting point (PWP), is the soil moisture level below which plants begin to wilt. The amount of water available to plants was calculated by subtracting the permanent wilting point from the field water capacity (Widtsoe and McLaughlin, 1912). Understanding PWP, which exerts a substantial influence on plant growth, nutrient acquisition, disease and pest resistance, and crop production, is crucial for designing soil moisture sensors that guarantee plants receive adequate water without squandering resources. By doing so, these sensors optimize water usage in agriculture. Therefore, measuring and monitoring soil moisture is an essential component of the best management practices to improve agricultural sustainability (Mundewadi et al., 2023).

An appropriate choice of soil moisture sensing system (SMSS) is essential for effective on-farm irrigation decision-making (Kojima et al., 2016). Although sensor suitability (e.g., to the type of soil and/or crop) is relevant to all users, performance accuracy and precision may be more important to scientific users, and operational feasibility may be more relevant for commercial agricultural users (Kukal et al., 2019). Operational feasibility includes cost and logistical aspects such as management, ease of operation, durability, life expectancy, and operational

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lifespan (Kukal et al., 2019; Schwamback et al., 2023). The utility of soil moisture sensing is challenged by i) sensor inaccuracy: some sensors may not provide accurate readings of soil moisture levels, especially if they are not properly calibrated or if the soil conditions are not suitable for the sensors (Adla et al., 2020; Kosasih et al., 2023). However, for some farmers and agronomists, precision is privileged over accuracy as consistent and reproducible outcomes facilitate better planning and resource allocation, which is especially crucial in areas with diverse hydrological regimes and distinct farming requirements (Gupta et al., 2024). By prioritizing precision, farmers can modify their strategies based on current data, identify discrepancies in field conditions, and optimize the utilization of resources, thereby emphasizing the value of precision in agricultural practices (Placidi et al., 2021); ii) sensor maintenance–some sensors may require frequent calibration, cleaning, or replacement, which can be time-consuming and expensive (Schwamback et al., 2023); iii) cost – high-quality soil moisture sensors can be expensive, which can limit their accessibility to low-income farmers (Schwamback et al., 2023); iv) environmental degradation through electrical and plastic waste in soil (Dahal et al., 2020); and v) replacement of sensor batteries–commercial environmental monitoring nodes are usually powered by batteries (Daskalakis et al., 2017). Addressing these challenges is critical for the widespread adoption of soil moisture sensors for agricultural water management, particularly in low-resource and remote areas.

This review is centrally motivated by the question of whether it is possible to have an SMSS that has all desirable attributes, i.e. it performs adequately, is operationally feasible (with respect to its cost and energy source) and is environmentally safe. This is necessary to overcome the problems of using SMSS due to lack of connectivity and resources (road, electricity, water resources) in remote or marginalized farms in developing countries, lack of material disposable facilities in developing countries, frequent climate fluctuations affecting efficiency of SMSS and lack of technical skills and financial conditions of smallholder farmers (Saleh et al., 2016). This review investigates the state-of-the-art in situ SMSS, highlighting the advances in low-cost sensors and sensing systems, off-grid ambient energy based SMSS, and biodegradable SMSS. The challenges and possibilities for the development and adoption of sensing systems that "has it all" in the agricultural water sector are then discussed, analyzing the trade-offs between sensor performance, operational feasibility, and environmental safety.

2. Literature review and search criteria

A literature search was carried out using abstract and citation databases, including Scopus for peer-reviewed articles published in English and comprising the fields "article title"; "abstract"; and "keywords". The basic query structure used for searching articles was (("low cost") OR ("off grid") OR ("biodegrad*")) AND (("soil moisture sensor" OR "soil humidity sensor")) AND ("agricultur*" OR "farm*"). The eligibility criteria for studies covered by the review comprised journal articles and conference papers published in English within the last ten years (2014–2024) to ensure the inclusion of recent and up-to-date research findings. In total 130 articles were found in Scopus, 57 articles found in Web of Science and 60 articles were found IEEE Xplore digital library. These articles Zotero Software was used for managing the articles. After removing the duplicates and irrelevant articles 77 papers were selected for reviewing based on the above query. In total 115 articles were considered for this review paper.

The majority of the studies reviewed were conducted in Asia and Europe, with India and the United States of America leading the way in terms of the number of studies conducted on a country-by-country basis (as indicated in Table 1). However, it is important to note that the representation in the table below does not necessarily reflect the actual number of studies conducted in each region.

Given the study scope and data acquisition requirements, original studies with the following foci were eligible for inclusion: 1) low-cost sensors categorized based on their purchase prices, 2) sensors powered by renewable power sources, and 3) biodegradable sensors.

Table 1
Regions in which literature review studies were conducted (N=total number of studies in a region).

Region	N	Specific countries
Asia	91	India (51), China (8), Indonesia (5), Malaysia (5), Thailand (4), Bangladesh (3), Pakistan (3), Japan (2), Philippines (2), South Korea (2), Turkey (2), Iraq (1), Saudi Arabia (1), Sri Lanka (1), Lebanon (1)
Europe	33	Italy (7), Spain (6), Germany (5), Netherlands (4), France (2), Romania (2), Hungary (1), Bulgaria (1), Sweden (1), United Kingdom (1), Ireland (1), Austria (1), Serbia (1)
North America	20	United States of America (19), Canada (1)
South America	7	Brazil (5), Ecuador (2)
Africa	7	Nigeria (2), Tunisia (2), Morocco (1), Kenya (1), Egypt (1)
Australia/ Oceania	4	Australia (4)

3. Fundamentals of soil moisture sensing

Soil moisture sensing involves the understanding of physical, chemical, and biological processes that influence soil moisture content and the different techniques used to measure it (Kosasih et al., 2023). Physical factors such as soil texture, structure, porosity, compaction, and temperature influence the movement and storage of soil moisture, and the soil moisture sensor accuracy. Chemical factors, such as soil pH and salinity, can affect the electrical conductivity and dielectric properties of soil, which are important parameters for some soil moisture sensors. Biological factors, such as organic content, can also affect soil moisture sensing, as microbial activity and plant roots can influence soil water holding capacity and porosity. Additionally, plant residues and other organic matter in the soil can affect soil moisture sensing by altering the electrical conductivity and dielectric properties of soil (Topp et al., 2008; Wenwu et al., 2018; Zhu and Lin, 2011).

3.1. Existing soil moisture sensing techniques

Soil moisture sensing can be categorized as gravimetric, volumetric, and potentiometric techniques (see Fig. 1). Gravimetric and volumetric methods directly estimate the soil water content, whereas potentiometric methods measure the electrical potential difference between two electrodes inserted into the soil.

The gravimetric technique is the oldest technique, and involves weighing a soil sample before and after oven drying to determine the moisture content.

The thermal volumetric technique directly measures the water content by measuring the water mass lost after oven-drying an undisturbed soil sample collected using a core sampler or tube auger. Nuclear techniques measure soil moisture indirectly by analyzing radiation-soil interactions. Neutron scattering techniques use a radioactive probe and helium-3 detector to estimate soil water by counting the thermal neutrons thermalized by hydrogen in the soil. The gamma ray transmission method uses a radioactive source, such as 137Cs, to emit γ-rays, and the energy of the γ-rays transmitted through the soil is used to estimate soil moisture content. Nuclear magnetic resonance (NMR) non-invasively estimates soil moisture by applying magnetic fields to the ground and detecting changes caused by hydrogen atoms in the soil. NMR logging can analyze hydrogen-containing fluid dynamics in porous media and detect soil moisture in situ. Cosmic-ray neutron sensing (CRNS) probes measure fast-moving neutrons in the soil and air to monitor soil moisture (Gianessi et al., 2021; Mukhlisin et al., 2021).

More recently, soil moisture sensing techniques have been developed to sense soil electrical properties (different from their electrochemical properties) including the natural electric field (electric potential), resistance (conductivity), electro-osmosis, and dielectric constants of

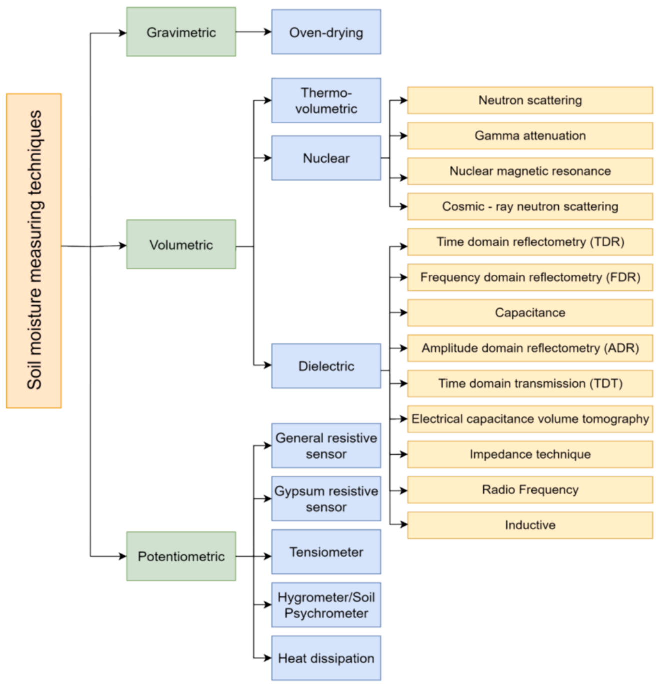

Fig 1. Soil moisture measuring techniques modified from Adla et al., 2020; Mukhlisin et al., 2021; Nikolov et al., 2021.

soils (Yu et al., 2021). Dielectric techniques measure the dielectric constant of soil, a characteristic that changes with soil moisture (Zeni et al., 2015). Time-domain reflectometry (TDR) is a method of determining the apparent permittivity of soil by measuring the time it takes for an electromagnetic pulse to travel through parallel electrodes inserted into the soil. The apparent permittivity of water, which is approximately 80 (unitless), is significantly larger than that of other soil constituents, which typically range from 1 to 12 (unitless). As a result, the apparent permittivity of soil is strongly correlated with soil moisture (Kojima et al., 2016). Frequency Domain Reflectometry (FDR) based sensors, measures the frequency change of radio frequency (RF) signal in soil induced by moisture change (Chang et al., 2022; Oates et al., 2017). Capacitance sensors release electrical charge into the soil and measure the soil dielectric permittivity (Feng et al., 2022). Time domain transmission (TDT) measures electromagnetic wave propagation through soil to determine moisture content. Information obtained from the real and imaginary parts of the complex admittance, conductance, and susceptance can be used to determine material properties. Radio frequency (RF)-based sensors gauge soil moisture levels by assessing the attenuation or propagation velocity of radio frequency signals traversing the soil medium (Chen et al., 2022). Inductive sensors use electromagnetic induction to measure the soil moisture. They emit an oscillating electromagnetic field into the soil, which induces alternating currents. These currents generate a secondary electromagnetic field that is detected by the sensor. The characteristics of this secondary field provide information on the apparent electrical conductivity (ECa) of the soil, which is influenced by its moisture content (Basterrechea et al., 2021; Calamita et al., 2015; Tian et al., 2022). Potentiometric soil moisture monitoring measures the electrical potential difference between the electrodes, which is dependent on soil conductivity. Resistive sensors measure the electrical resistance of the soil, which is influenced by its water content (Kosasih et al., 2023). Electrical resistance blocks, often referred to as gypsum blocks, feature two embedded electrodes within the gypsum block itself. When these blocks are placed in soil, the resistance between the electrodes changes in response to the movement of water, which is influenced by soil moisture levels (Zeni et al., 2015). A tensiometer involves measuring the water movement in porous materials that are in contact with the soil to determine the soil moisture energy (Yu et al., 2021). Heat-dissipating sensors capitalize on the fact that wet soil is capable of dissipating heat more rapidly than dry soil, and they employ this phenomenon to quantify the rate of temperature increase when a heat source is applied (Ding and Chandra, 2019).

All the techniques mentioned above have their own set of advantages and disadvantages, which were thoroughly discussed in detail by Rasheed et al. (2022).

4. Components of soil moisture sensing system (SMSS)

Monitoring and management of soil moisture influence resource management in agriculture (e.g., water and fertilizers). But its cost can be a major limiting factor for adoption among farmers (Ferrarezi et al., 2015; Schwamback et al., 2023). The design of affordable SMSS essentially implies the cost-effectiveness of each of its components. SMSS typically estimate soil moisture indirectly by detecting other soil properties (Zhou et al., 2019) and necessitates the inclusion of various components (Vandôme et al., 2023) in SMSS such as sensor, microcontroller, power source, communication module, software component and supporting hardware as shown in Fig. 2 (Ferrarezi et al., 2015).

A sensor is a device that measures a property that is linked to soil moisture. A microcontroller is a small, low-power computer that can control and read sensors, process sensor data, and control the operation of the system. A power source provides electricity to the system (e.g., batteries, solar panels, AC power, etc.). A communication module enables the system to transmit data to an external device such as a data logger, computer or smartphone (Josephson et al., 2020). The software component may include firmware and software for applications, such as data processing, database management, data (en-)coding, microcontroller control, and sensor data processing. Additionally, software components can be involved in the user interface and cloud platforms to host data (Brinkhoff et al., 2018). The supporting hardware includes transistors, resistors, capacitors, and connecting wires, which can receive and display data from the system for later use (Ferrarezi et al., 2015).

Some of the available soil moisture sensor was connected to a microcontroller (light green line in Fig. 2) and external data storage device. It may also be connected to a communication module that wirelessly transmits sensor data to the network server (blue line in Fig. 2). Sensors, microcontrollers, and communication devices use hardware (black dotted line in Fig. 2) to connect and store soil moisture data in external

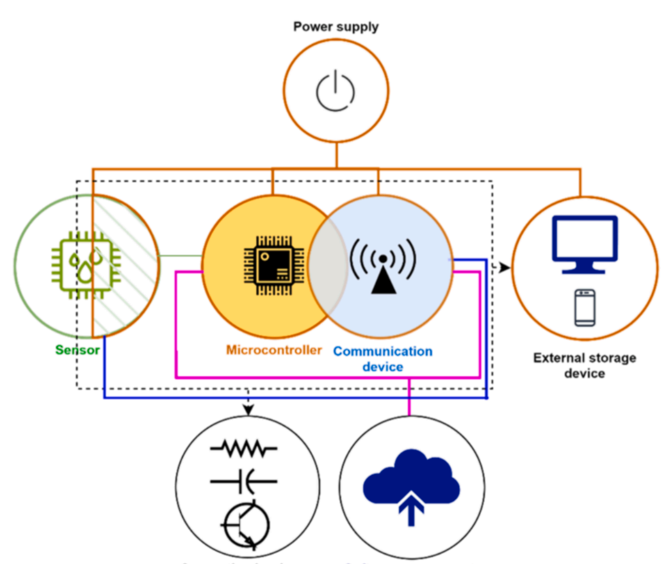

Fig 2. Various components of a soil moisture sensing system (SMSS) modified (Ferrarezi et al., 2015).

storage. Access to stored data and data communication is usually associated with software components. Components, such as sensors (with some exceptions depicted with green hatched lines in Fig. 2), microcontrollers, and communication devices, require a power supply (shown with brown colour line in Fig. 2). The specific components of an SMSS depend on its design and purpose. More accurate sensors and sensing systems tend to be costly and vice versa (Chang et al., 2022). When designing a low-cost SMSS, some important considerations include sensor and microcontroller selection while maintaining the accuracy and reliability of the data. The choice of data storage, such as cloud platforms and Secure Digital (SD) memory cards, also influences costs, particularly in harnessing the potential of big data in agriculture in a real-time manner. Furthermore, low-power sources and low-cost wireless communication modules can reduce operational and maintenance (O&M) costs and enable deployment in remote areas that lack adequate infrastructure (Feng et al., 2022; Mundewadi et al., 2023). O&M costs can also be lowered by reducing the need of technical expertise and skilled labor required in installing, operating, and maintaining SMSS (Placidi et al., 2023a). Finally, capital is also required to deploy SMSS at larger spatial and temporal scale, to replicate and scale such solutions (Feng et al., 2022; Srbinovska et al., 2015).

4.1. Low-cost soil moisture sensor

The cost of a soil moisture sensor depends on factors, such as its measurement technique (Adla et al., 2020), accuracy (Schwamback et al., 2023), range of connectivity for wireless communication (Feng et al., 2022), durability (Schwamback et al., 2023), and manufacturing costs (Yu et al., 2020). More accurate soil moisture sensors tend to be more expensive owing to their high-quality sensor components (Mundewadi et al., 2023), fabrication methods (Farooqui and Kishk, 2018), and manufacturing processes (Biswas et al., 2022). Additionally, sensors that can measure soil moisture over a wider range of soil water content (Nagahage et al., 2019) have higher sensing volumes, longer life (Brinkhoff et al., 2018), faster response times, and shorter recovery times, and tend to be more expensive because they require more sophisticated calibration and validation processes (Jain et al., 2020). Sensors that can connect to the Internet or a wireless network to send data to a remote server or cloud-based system, or those that are built to withstand harsh environmental conditions (such as extreme temperatures and exposure to chemicals) can be more expensive than standalone sensors (Mundewadi et al., 2023). Finally, economies of scale achieved through higher production volumes also impact the overall costs (Manjakkal et al., 2021).

Current state-of-the-art commercially available soil moisture sensors may be cost-prohibitive, time-consuming to install, labor-intensive, and restrict the deployment density to approximately one device per field (Ferrarezi et al., 2015; Iqbal et al., 2020; Schwamback et al., 2023). Low-cost soil moisture sensors are often designed using less expensive materials, such as plastics, instead of more expensive materials, such as metals (Chanwattanapong et al., 2021; Iqbal et al., 2020). The term ‘low-cost sensor’ has been used subjectively in the literature in the context of the purchase prices of sensors, and a large variation in sensor costs has been reported (from < 1 USD to 300 USD per sensor) (Adla et al., 2020; Dahal et al., 2020; Yu et al., 2021; Zhou et al., 2019). According to Adla et al. (2020) and Biswas et al. (2022), capacitive sensors are classified as low-cost as they acquire soil water content at low cost with high precision and they also meet the requirements of wireless sensor network (WSN), and resistive sensors are classified as very low-cost sensors. In addition, low-cost sensors have been developed based on TDR, electrical impedance spectroscopy (EIS) (Umar and Setiadi, 2015), mutual inductance (Parra et al., 2020, 2019; Tessmer and Aschenbruck, 2023), dual-probe heat pulses (Kalita et al., 2016), soil-moisture detection, and heat dissipation techniques (Saeed et al., 2019). They were also developed based on radio-frequency technology (Chang et al., 2022).

4.2. Other components in low-cost SMSS

The other software and hardware components of SMSS (Fig. 2) are interconnected; hence, their respective costs must also be considered to achieve overall cost-effectiveness. Table. 2 provides information about the manufacturers and unit prices of various open-source and commercially available software and hardware components that can be used for designing low-cost soil moisture systems.

4.2.1. Hardware components

4.2.1.1. Microcontrollers. Software and hardware components for microcontrollers are often developed as packages available under both commercial and open-source platforms (Bachuwar et al., 2018). These hardware may cost between approximately 3 USD (e.g., PIC, ATMEGA328P) and 11 USD (e.g., ARM Cortex M−4).

Commercial microcontrollers, such as ESP32, can support Wi-Fi and Bluetooth connectivity, consume low power, and still perform adequately in sensing soil moisture in automated solar irrigation pumping systems (Abba and Lee, 2019; Borah et al., 2020). The application of Internet of Things (IoT) technology in farms through Wireless Sensor Networks (WSNs) can substantially increase the adoption and upscaling of SMSS, by real-time communication of data from multiple interconnected sensors (Iqbal et al., 2020; Placidi et al., 2023a; Kumar et al., 2014). The ARM Cortex M−4 core and ATMEGA328P software and hardware are proprietary microcontroller products that are also included in other commercial products. For instance, STM32 is a family of microcontroller chips based on the ARM Cortex-M cores, and is known for its versatility and extensive range of supported features in farming application (Sulthoni et al., 2016) and ATMEGA328P has been used for soil moisture applications in horticulture. (Abba and Lee, 2019; Bachuwar et al., 2018; Borah et al., 2020; Devapal, 2020; Saleh et al., 2016; Umar and Setiadi, 2015; Zeni et al., 2015).

However, commercial microcontroller products generally have proprietary designs that are unavailable for public access. The recent advent of open source as a disruptive phenomenon has improved the usage,

Table 2
Manufacturer and cost of hardware and software components used in low-cost sensing systems.

Index	Component	Manufacturer	Cost ($/unit)	Ref.
Hardware components				
A)	**Only microcontroller**			
1	Arduino	Arduino	12 –25	(Abba and Lee, 2019; Ferrarezi et al., 2015)
2	STC89C52RC	STC Micro	1.12	(Nagahage et al., 2019)
3	Raspberry Pi	Raspberry Pi Foundation	15	(Feng et al., 2022)
B)	**Only communication module**			
1	Wireless Fidelity (WiFi) (ESP8266)	Ai-Thinker	1.79	(Nagahage et al., 2019)
2	Long range (LoRa SX1276)	Semtech	20 Euro	(Placidi et al., 2023a)
C)	**Both (Microcontroller + communication module)**			
1	ATMEGA328P	Microchip Technology (previously Atmel Corporation)	~3	(González-Teruel et al., 2019)
2	ESP32	Espressif Systems	~10	(Borah et al., 2020)
Software components				
1	Raspberry Pi OS	Raspberry Pi Foundation	Free	(Feng et al., 2022)
2	Arduino IDE	Arduino	Free	(de Melo et al., 2023)

modification, and distribution of such solutions. The Arduino is a microcontroller board based on the ATMEGA328P chip for sensing soil moisture (Abba and Lee, 2019; Chang et al., 2022; Iqbal et al., 2020; Jamroen et al., 2020; Schwamback et al., 2023; Vandôme et al., 2023; Zeni et al., 2015). Raspberry Pi is a primarily open-source single-board computer produced by the Raspberry Pi Foundation, which has been used to sense various parameters including soil moisture (Bachuwar et al., 2018; Feng et al., 2022; Iqbal et al., 2020; Kiv et al., 2022). Also, these microcontrollers provide a robust and versatile foundation for data logging technologies by interfacing with various sensors (Iribarren Anacona et al., 2023) and enabling accurate data acquisition and synchronization through real-time processing (Bhadola et al., 2022). Their low power consumption suits battery-operated, portable data logging systems in remote, off-grid locations (Bhadola et al., 2022). They can locally store data on SD cards and transmit it wirelessly for analysis. Additionally, microcontrollers can be tailored to specific data logging needs by adjusting sampling rates, data types, and the number of channels (Kerr and Rogers, 2023). Integration with components like amplifiers and analog-to-digital converters enhances functionality and accuracy. Their cost-effectiveness makes them accessible in developing and underdeveloped countries where expensive data loggers are unaffordable (Bhadola et al., 2022).

4.2.1.2. Communication modules. Table 2 depicts various communication modules utilized in low-cost sensing systems. Notably, the table indicates that certain communication modules, such as ESP32 and ATMEGA328P, are integrated into microcontrollers. Two key factors in selecting a communication module are power consumption and range (of effective communication) (Briciu-Burghina et al., 2022). Other factors, such as the data transfer rate (of transmission and reception) (Kumar et al., 2014) and form factor (the module's physical shape and its dimensions) (Gonzalez-Teruel et al., 2022), along with the power consumption and range characteristics, contribute to the overall module cost (Vannieuwenborg et al., 2018). Based on their range, communication modules can be classified into contact range (0-10 m), short-range (10-100 m), short/medium-range (100-1000 m), medium-range (~5-10 km), and long-range (up to 100 km) modules (Brinkhoff et al., 2018; Chaudhari et al., 2020). Some SMSS may only require sensors to transmit over a relatively short range to the external storage device, for which short- and medium-range communication modules are sufficient.

More recently, communication devices have transcended their traditional roles and evolved into versatile sensors, transforming the interaction of humans with their surroundings. Among contact and medium range solutions, Bluetooth Low Energy (BLE) is a low-power, wireless communication technology that is designed for devices that need to communicate with each other in sensing soil moisture (Bachuwar et al., 2018). ZigBee is a module frequently used in WSN applications (Abba and Lee, 2019; Briciu-Burghina et al., 2022; Brinkhoff et al., 2018; Deng et al., 2020; Lloret et al., 2021) and WiFi has also been used for soil moisture sensing (Abba and Lee, 2019; Ding and Chandra, 2019; Nagahage et al., 2019). Open-source integrated solutions such as Raspberry Pi and Arduino have already been discussed. Radio-Frequency Identification (RFID) and NFC tags are communication tags and use radio waves to identify and track objects equipped with tags containing microchips and antennas to collect and transmit data (Borah et al., 2020; Chang et al., 2022; Chen et al., 2022; Daskalakis et al., 2017; Dey et al., 2015; Iyer et al., 2022; Kim et al., 2014; Kiv et al., 2022; Zaccarin et al., 2023; Zeni et al., 2015). These tags have been used for measuring soil moisture sensor data. Near-field communication (NFC) tags are a form of RFID tags that communicate over relatively shorter ranges, enabling two-way communication between devices such as smartphones. NFC tags have advanced features and can interact with connected devices, and have been used widely in industries and in soil moisture sensing (Boada et al., 2018). Usually these tags are embedded in objects and RFID readers are used to retrieve soil moisture data from these tags. However, when these solutions need to be upscaled via WSNs and/or used in remote locations, a combination of long-, medium- and short-range communication modules may be required.

Cellular GSM modules are cellular modules from u-blox and other manufacturers that allow devices to access the internet to receive and transmit soil moisture data (Gianessi et al., 2021). By contrast, XBee is a wireless module known for its long-range capabilities (Kumar et al., 2014). LoRa is a low-power, low bandwidth wireless communication module that can communicate over ranges of 10 km, has a battery lifetime of months, and has been used for soil moisture sensing applications with strict power requirements (Bertocco et al., 2023; Chang et al., 2022; Chanwattanapong et al., 2021; Kiv et al., 2022; Vandôme et al., 2023; Afridi et al., 2023).

The selection of a communication module for low-cost sensing depends on the purpose, performance, and operational feasibility considerations of such a system.

4.2.2. Software components

The aforementioned hardware requires software components for operation. Two significant examples of open-source products that combine both microcontrollers and communication capabilities are Raspberry Pi and Arduino (Schwamback et al., 2023). The Arduino Integrated Development Environment (IDE) is a cross-platform application that enables users to write and upload code to Arduino compatible microcontroller boards (Borah et al., 2020; González-Teruel et al., 2019). It provides a user-friendly interface and extensive community support for editing and debugging code, as well as a library of functions and examples to start with programming Arduino boards for designing SMSS (Vandôme et al., 2023). It can be used for the interface of various microcontrollers and for storing data. The Raspberry Pi OS (free and open-source Linux based operating system for Raspberry Pi microcontrollers) has also been used for soil moisture monitoring (Feng et al., 2022; Iqbal et al., 2020; Zeni et al., 2015).

5. Off-grid ambient energy based SMSS

The low-cost SMSS described in Section 4 rely on electronic components that require external energy sources, such as grid-based electricity (Abba and Lee, 2019; Chen et al., 2022). Various advancements in energy generation and consumption hold promise for using such energy sources, including (i) improved battery technology resulting in longer battery life, (ii) lower power consumption because of optimized data communication via lightweight messaging protocols and low-power processors, and (iii) low-power processing technologies (Abba and Lee, 2019; McGrath et al., 2013; Zeni et al., 2015). However, access to energy grids is particularly limited in remotely located farms, off-grid homesteads, and mobile applications, where off-grid energy sources could be potentially useful (Lloret et al., 2021; Zeni et al., 2015). Additionally, recently developed wireless sensor networks used in SMSS require a continuous energy supply for continuous and lifetime operation for each.

Node (Abba and Lee, 2019; Iqbal et al., 2020; Paz Silva et al., 2023; Sudarmaji et al., 2020). In addition to cost, the above factors limit the scalability of sensing systems. Hence, in situ energy generation by harvesting energy from ambient energy sources can be vital to power autonomous off-grid SMSS (Chatterjee et al., 2023; Faheem et al., 2019; Gill and Hasan Albaadani, 2021).

5.1. Ambient energy sources

The four main ambient energy sources naturally or artificially present in the environment are: radiant, biochemical, thermal, magnetic, and mechanical (Chatterjee et al., 2023). This review focuses on chemical and radiant energy sources used in SMSS. Table 3 lists some relevant examples of ambient energy with their overall energy costs.

Table 3
Ambient energy sources used in review of SMSS and their overall energy cost.

Index	Ambient energy	Source	Renewable energy (Yes/No)	Examples	Cost	Ref.
1	Radiant	Solar radiation	Yes	Solar Photovoltaic	0.83 $/kW h	(Baurzhan and Jenkins, 2016)
		Radio Frequency	No	RFID	tag cost + reader cost	(Zare, 2010)
				NFC	tag cost + smartphone cost	(Arcese et al., 2014)
2	Chemical	Chemical reactions	Yes	Battery	273 $/kWh	(Curry, 2017)

5.2. Ambient energy sources for soil moisture sensing applications

5.2.1. Radiant energy

Radiant ambient energy encompasses electromagnetic radiation in the environment, such as visible light, infrared radiation, and radio waves, which can be converted into electricity for various uses. The sun, a major energy source, emits visible light, infrared, and ultraviolet radiation, harnessed through technologies like solar photovoltaic (PV) cells and radio frequency (RF) energy harvesters. RF radiation, with wavelengths longer than visible light, is also utilized in cellular communication (Tan and Panda, 2010).

5.2.1.1. Solar energy. Radiant ambient energy applications, such as solar photovoltaic (PV) cells, are constructed from semiconductor materials that can absorb sunlight and generate electric current. Solar PV energy has been extensively used to power wireless soil moisture sensors and in greenhouses. Solar photovoltaic (PV) systems require batteries to function effectively in off-grid regions, as solar energy is intermittent due to day-night cycles and weather conditions. These variations necessitate energy storage solutions to ensure a continuous power supply. The batteries within the solar panels store excess energy generated during peak sunlight hours, which can then be used during periods of low or no sunlight, thus maintaining the uninterrupted operation of wireless sensor networks (WSNs) (Dorel et al., 2023). Many studies have been conducted to measure soil moisture using solar energy, such as Brinkhoff et al. (2018), de Melo et al. (2023), Devapal (2020), Schwamback et al. (2023), Afridi et al. (2023) and Zeni et al. (2015).

5.2.1.2. Radio-frequency. In radio frequency ambient energy sources, RFID and NFC tags are utilized in SMSS. RFID devices comprise readers and tags. Readers emit magnetic fields or electromagnetic waves, and tags respond to reader commands. Tags can be either passive, powered by the reader (Kim et al., 2014), or active, with their own power sources. RFID tags can harvest energy to power external sensors or microcontrollers. Although low-powered, these tags can be used in WSN through wake-up signals that activate sensors only when needed, conserving energy (Jain and Vijaygopalan, 2010). WSN nodes can switch between active and sleep modes, allowing tag data to be read even when some nodes are inactive (Li et al., 2008). Tag reading protocols can be adjusted to involve multiple RFID-enhanced sensor nodes, distributing the energy load (Klair et al., 2008). RFID tags powered by renewable sources, such as solar panels, can efficiently drive low-power sensors (Ferdous et al., 2016). Previous studies have employed tags in SMSS (Chen et al., 2022; Daskalakis et al., 2017; Feng et al., 2022; Kim et al., 2014). The RFID reader has been identified as a potential radio frequency power source for sensors (Daskalakis et al., 2017).

5.2.2. Chemical ambient energy

Chemical ambient energy can be sourced from natural reactions in the environment, such as those in water, soil, and living organisms (Ahmed and Kakkar, 2017) offering significant potential for clean and sustainable applications (Mahmoud et al., 2022; Srikanth et al., 2018). Methods to harness this energy include fuel cells, batteries, and biological processes. Fuel cells convert chemical energy into electrical energy without combustion, making them a cost-effective alternative to traditional batteries, especially in remote and off-grid areas (Wilberforce et al., 2016). Microbial fuel cells, which generate electricity from waste products via certain bacteria, provides energy autonomy in off-grid regions (Rossi et al., 2017). Batteries generate energy by converting chemical energy into electrical energy, creating an electric current to power devices (Schmidt-Rohr, 2018). Additionally, electricity can be harnessed from the natural voltage differential in soil to convert chemical energy into electrical energy (Borno et al., 2021).

5.2.2.1. Batteries. Batteries are crucial in harnessing ambient energy sources such as solar to provide reliable and sustainable energy (Brinkhoff et al., 2018; Devapal, 2020; Sudarmaji et al., 2020). These batteries are energy storage systems, capturing excess energy generated during times of high solar or wind activity, and then releasing it when demand exceeds supply. This ability to store energy enables off-grid communities to maintain a consistent supply of electricity, regardless of the variability of ambient energy sources (de Melo et al., 2023). Various studies have used batteries as energy source like Li-ion batteries (Bertocco et al., 2023; Paz Silva et al., 2023; Vandôme et al., 2023), solar (photovoltaic-PV) powered batteries (Patrizi et al., 2022), rechargeable batteries (Chen et al., 2022; de Melo et al., 2023; Feng et al., 2022; Ferrarezi et al., 2015; Vandôme et al., 2023), normal cell batteries (Schwamback et al., 2023) and 2000 mAh power bank (Kulmany et al., 2022). Moreover, solar panels can serve as a source of power to recharge battery chargers, or they can be integrated with inverters or other hardware devices (Brinkhoff et al., 2018). These low-power, battery operated SMSS work with various sensing techniques, including capacitance (Ferrarezi et al., 2015; Kojima et al., 2016; Vandôme et al., 2023). The operational life of battery operated sensors/transmitters is expected to be of the order of several years, with PV panels energizing the battery during the daytime (Zeni et al., 2015). Backscatter tags working on 4 AA size batteries have had battery lifetimes of upto 15 years (Josephson et al., 2020). Solar charged rechargeable batteries (even run off disposable batteries) within a SMSS with design choices to minimize power consumption have powered SDI-12 capacitance-based soil moisture probes for the duration of the entire growing season (González-Teruel et al., 2019).

The aforementioned ambient energy sources each have distinct advantages and limitations. Common benefits include their status as promising renewable and sustainable energy sources, requiring low maintenance, being non-toxic, and eco-friendly. However, the materials for construction are expensive. Solar radiation sources offer theoretically infinite power with no air and water pollution, but they require continuous sunlight and involve high initial storage or backup costs. Solar-powered batteries for SMSS are easy to install, provide high power output, and have long lifespans, yet they are not fully renewable, environmentally unfriendly, and need regular replacement. Radio frequency energy sources are cost-effective, compact, durable, and suitable for low-power devices like wireless sensor networks and RFID tags, but they deliver limited output power and can be disrupted by other electronic devices. NFC tags specifically have a short read range.

Ambient off-grid energy sources facilitate decentralized sensing systems but may increase overall costs. Key factors in selecting energy sources for SMSS include minimizing the levelized cost of electricity (LCOE), which compares power generation costs over time. High initial capital, installation, and maintenance costs for solar panels and generators are significant drawbacks. Their limited capacity also complicates charging multiple sensors simultaneously due to low power output. Despite favorable LCOE metrics, off-grid sources face institutional, regulatory, and human resource challenges. Weather variability, such as solar PV cells' dependence on local radiation, further impacts reliability and applicability. Studies have reviewed and experimentally examined the energy needs of various soil moisture sensor modules with different microcontroller units, highlighting variations in energy consumption per measurement (mW.s), crucial for selecting energy sources in remote areas (Come Zebra et al., 2021; Shen et al., 2020).

In addition to the reliability and life expectancy of sensing systems, these considerations may thus trade off with scalability and hence influence the overall impact of such solutions.

6. Biodegradable sensors

Technological solutions such as SMSS including IoT systems offer promising improvements in water-use efficiency in precision agricultural systems. At the same time, they may cause environmental degradation (e.g., soil pollution via electrical and plastic waste) (Dahal et al., 2020). To reduce the impacts of these inherent contradictions, solutions need to be designed towards minimal ecological footprints. In this context, SMSS with biodegradable sensors have the potential for more efficient agricultural input usage over entire cropping seasons and with lower detrimental impacts on the environment (Dahal et al., 2020). These sensors provide information about the moisture levels in the soil and are designed to degrade over time in the soil environment, which remain functional for extended periods in the presence of soil microbes, and then fail rapidly through electrode decomposition after the encapsulant (a covering that is applied to an electrode surface) sufficiently degrades (Dahal et al., 2020).

These sensors work through the interaction between soil water and sensing materials, such as electrolytes, semiconductor ceramics, and polymers. These sensing materials can be classified as biodegradable or nonbiodegradable. Biodegradable materials that naturally disappear in their respective environments can be used to manufacture biodegradable (or bioresorbable) sensors. These materials include polymers, copolymers, silicon-based materials, proteins and metals. Biodegradable polymers can be either natural or synthetic. Natural biodegradable polymers, also called biopolymers, are further classified into biopolymers directly extracted from biomass (plant derived polymers and animal derived polymers) and biopolymers produced by natural or genetically modified organisms, whereas synthetic polymers are manufactured chemically (Samir et al., 2022). Plant derived polymers such as cellulose based materials, for example paper have been used as substrates for designing soil moisture sensors by Kim et al. (2014), balsa wood (Dahal et al., 2020; Sui et al., 2021) and animal derived polymers such as beeswax, soy wax, Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) (Dahal et al., 2020).

Synthetic polymers are chemically synthesized from sources such as corn starch and cassava roots and are subdivided into polymers synthesized from bio-derived monomers (water-based monomers) and polymers synthesized from synthetic monomers (petroleum-based monomers) (Samir et al., 2022) (eg: wax blends and PHBV(Dahal et al., 2020)). Polylactic acid, which is a synthetic polymer, has been used to fabricate fully biodegradable capacitive soil moisture sensors by printable conductive pastes comprising poly(lactic acid) (PLA) as binder while Tungsten was used as a conductor (Atreya et al., 2020). Such composite conductors provide enhanced stability in various applications including agriculture (Atreya et al., 2020). It can be concluded from this study that the composite conductors give stability to the sensors.

In addition to the above biodegradable polymers, (Yu et al., 2020) proposed and demonstrated a novel corrosion-resistant, embeddable, open-end coaxial cable soil moisture sensors using moisture-sensitive - polyvinyl alcohol (PVA) film on oxide-based thin-film transistors.

In addition to the above soil moisture sensors, the utilization of certain humidity sensors has also been evaluated in this study, in light of the fact that they possess the potential for environmental application such as soil moisture (Abba and Lee, 2019; Kalita et al., 2016; Neto et al., 2022; Yu et al., 2020; Zaccarin et al., 2023).

After designing a biodegradable sensor, it is also necessary to determine the biodegradation time of various sensors prepared using biopolymers. Different studies have described the various stages of degradation (Jain et al., 2020), tests for biodegradability (Kasuga et al., 2024), calculations about degradability rate (Dahal et al., 2020), and assessment of degradation kinetics of component materials (Dahal et al., 2020), all of which can help to design application-specific sensors.

7. Selecting a "perfect" soil moisture sensing solution: low-cost, off grid, biodegradable

7.1. Current challenges in soil moisture sensing systems

There are challenges in employing SMSSs associated with each of the reviewed factors. Low-cost SMSS have accuracy issues and generally need frequent soil- and site-specific calibration (Chang et al., 2022; González-Teruel et al., 2019; Mundewadi et al., 2023). Also, they either need continuous power supply or have recurrent battery and other maintenance costs (de Melo et al., 2023). Open-source components are generally available individually as commercial products and often need to be assembled in-house (Vandôme et al., 2023). The process of assembling these components restricts any optimization that can be done on the size of the overall system, as well as reduces system lifetime due to the lack of rigorous laboratory testing capabilities (Gopalakrishnan et al., 2021; Wu and Liu, 2012). This increases overall costs and reduces viability for wide-area distribution (Pal et al., 2022).

Remote solutions powered by off-grid ambient energy sources also tend to be challenged by the processes involved in the manufacture and disposal of the associated electronic components. In fact, such solutions may counterproductively harm environmental health to some extent while claiming to enhance environmental sustainability. Waste management infrastructure for collecting and recycling used lead-acid batteries, can have up to 50 % lead losses already in the recycling phase within the informal sector (Batteiger, 2015). In developing economies, disposal of batteries typically involve landfills and open garbage dumps (often associated with open waste burning) which adds to soil and air pollution (Hansen et al., 2022). The short (three to four years) working life of off-grid solar products leads to solar e-waste (Munro et al., 2023). Materials used in solar panels and batteries can have environmental and health impacts after use (Cross and Murray, 2018).

Biodegradable sensing systems are challenged by factors related to their degradation time as well as their degradability itself. There is a decrease in operational lifetimes in using laboratory tested sensors in complex biophysical environments and under mechanical stresses due to movements and deformations (Dahal et al., 2020; Zaccarin et al., 2023). Present day conductive traces used in these sensors also degrade through exposure to moisture, and research is needed to reduce this water-dependent degradation while maintaining adequate sensitivity to determine soil moisture (Atreya et al., 2020; Kojima et al., 2016). Surface roughness of cellulose paper creates challenge for sensor fabrication as it affects electrical properties (Iyer et al., 2022).

Many studies have combined one or more of the reviewed factors to design SMSSs, as outlined in Fig. 3. This Venn diagram lists various studies classified on the basis of the SMSSs use of low-cost components, off grid energy sources or biodegradable material. It is evident that a significant number of cost-effective SMSSs are commercially available and can be manufactured using affordable hardware and/or software components (blue circle); this review identified 69 such studies. On the other hand, 17 studies have explored soil moisture sensing powered by off-grid ambient energy sources (orange circle). Since the development of biodegradable sensors is a recent phenomenon, a relatively lower number of such studies (8) have been included in this review (green circle).

Among the intersecting areas, studies have also developed and applied low-cost SMSS that can operate using off-grid energy sources

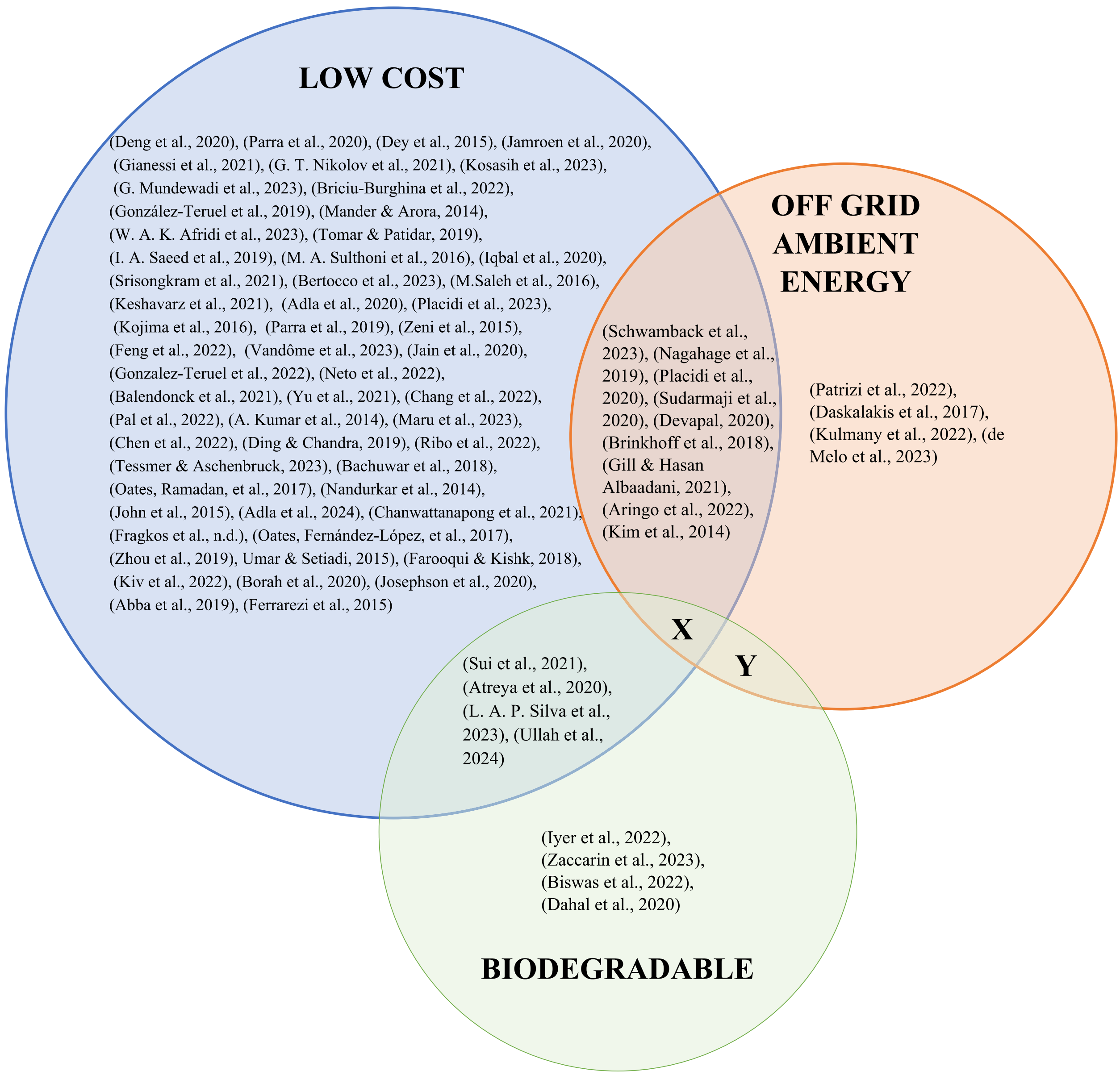

Fig 3. A Venn diagram representing the gaps in currently available literature on SMSS considering cost, off grid energy source-compatibility, and biodegradability.

such as solar power. 9 such studies have been identified in the corresponding area of intersection. Also, low-cost biodegradable soil moisture sensing has seen recent advances, and this review includes 4 such publications.

However, no studies of biodegradable soil moisture sensing powered by off-grid energy sources could be identified in this review (region Y). Consequently, there are no published studies on SMSSs which capture all the three aspects highlighted in this review (region X). These gaps in the literature reveal the possibilities for research and development in SMSSs, accounting for cost effectiveness, remote applicability, and environmental safety.

7.2. *Selecting a “perfect” soil moisture sensing system*

The choice of sensing system depends on the tradeoffs between multiple attributes to ’balance’ the overall system effectiveness. A commonly explored trade-off is between sensor cost and accuracy (Kojima et al., 2016). This tradeoff manifests from a larger, user-centric framework for selecting desirable SMSS that balance both sensor performance and operational feasibility (which subsumes cost considerations) (Kukal et al., 2019). Based on this review, a third aspect is suggested to be added to this trade-off – biodegradability. Fig. 4

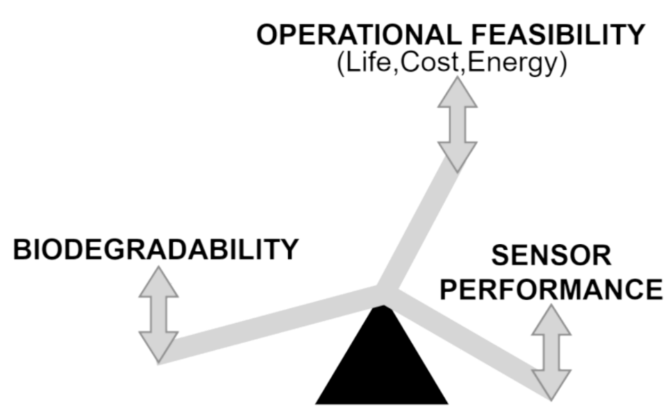

Fig 4. Conceptualizing the trade-offs based on operational feasibility (life, cost, energy requirement), sensor performance and biodegradability.

conceptualizes all these trade-offs as a three-way system to understand the multiple considerations when choosing an application specific SMSS. The arms represent sensor performance, operational feasibility, and biodegradability. Sensor performance involves accuracy, precision, measurement range, environmental sensitivity, and response time (Ullah et al., 2024). Operational feasibility includes aspects such as cost, size, durability, and power requirements (with impacts on telemetry, sensing, and logging costs) (Kukal et al., 2019). Biodegradability is quantified by the biodegradation time taken for the system components to naturally break down in the environment.

There is an indirect tradeoff between biodegradability and sensor costs; a sensing system's life expectancy is reduced by its inherent biodegradable properties (of "disappearing naturally in its respective environment"), consequently impacting long-term monitoring (owing to more recurrent sensor costs). However, aspects such as life expectancy of SMSS have not been extensively explored much in the literature. Some studies may report the sensor life expectancy (Schwamback et al., 2023); nevertheless, any effort towards sensor development and testing would benefit from well-designed, application-oriented investigations into the life expectancies of the sensors themselves and the SMSS they are a part of. Sensor manufacturers may not release protocols for such testing because of the proprietary nature of the information, but in the age of open science (Vicente-Saez and Martinez-Fuentes, 2018), it is desirable that both peer-reviewed and non-refereed efforts test life expectancies and share their protocols.

This exemplifies the complexity of selecting a suitable sensing system because of the tradeoff "balance." These attributes must be deliberately weighed with respect to each other and can be used within existing frameworks (e.g., (Kukal et al., 2019)). Overall, there is no perfect solution and the decision of choosing a suitable SMSS is essentially context-specific, with a purposeful management of these tradeoffs. For example, small-scale farmers who may be rainfed and have no access to data about their farms' soil moisture status maybe practicing subsistence farming, and need to maximize yield rather than water use efficiency. A low-cost decentralized system which can detect water scarcity would be more applicable here. Whereas in developed countries, large-scale contract farmers may prioritize resource (including water) use efficiency, to give them a profitable proposition because of economies of scale of their own production. In this case, they would prefer high-precision agricultural solutions which demand accurate sensing systems, even if they provide marginal information. This review can help to assess the right SMSS for diverse applications in the agricultural sector.

The gaps as identified by regions X and Y (Fig. 3) also imply that the corresponding tradeoffs have not been well explored. For example, if off-grid systems are not biodegradable then they may harm the environment as a result, disproportionately impacting resource-poor farmers (gap is identified by region Y in Fig. 3). Off-grid SMSSs use batteries and solar panels which contain harmful chemicals, and the disposal, recycling or reuse is a problem in developing countries, which is further accentuated by the diffused nature of the environmental harm (it being off-grid). Because of that these batteries are disposed of in landfills and open garbage dumps which cause soil pollution, soil erosion, and landscape change (Ellabban et al., 2014). Shorter (three to four years) working life of off-grid solar product leads to solar e-waste (Munro et al., 2023), which can have environmental and health impacts after use (Cross and Murray, 2018). All these should be considered before deciding the off grid ambient energy sources for SMSS. To enhance and ensure the accuracy of the perfect SMSS, various strategies can be implemented. These include universal and single-point calibration (Feng et al., 2022; Saito et al., 2022; Schwamback et al., 2023), integration of state-of-the-art sensor technologies, such as LTE signals (Kulmany et al., 2022), and utilization of LoRa signals, which have demonstrated an average error of 3.1 % (Chang et al., 2022). Additionally, a battery-free Wi-Fi tag system, such as SoilTAG, can be used to convert soil moisture changes into frequency responses, achieving an accuracy of 2 % within a 6-meter range and 3.64 % within a 10-meter range (Jiao et al., 2022). Furthermore, by improving the surface characteristics of sensor substrates (Iyer et al., 2022) and enhancing sensor trace quality (Iyer et al., 2022), as well as developing fully degradable intelligent radio transmitting sensors by encapsulating miniaturized resonating antennas in biodegradable materials, the accuracy of SMSS can be further improved (Gopalakrishnan et al., 2021).

8. Conclusions and ways forward

Commercially available low-cost SMSS may not provide accurate and reliable soil moisture estimates, leading to incorrect irrigation (and other) management decisions as it is influenced by soil characteristics, such as texture, temperature, bulk density, and salinity. The calibration functions provided by sensor manufacturers are typically developed under laboratory conditions and may not be accurate for field applications but can be improved by site-specific calibration. These sensors have shorter lifetimes owing to faster wear and tear of their sensing elements. This may limit their measurement ranges and reduce their suitability for all soil types and depths. This can be addressed to an extent by site-specific calibration and regular maintenance at the cost of other resources (e.g., time and human resources). Furthermore, low-cost sensing may be more susceptible to interference from other factors such as temperature, humidity, and soil salinity, which can affect data accuracy This can be countered by rigorous laboratory and field testing and the corresponding methodological innovations to compensate for environmental sensitivity. As a result, although such methods can produce lower quality data than more expensive sensors, there are techniques to improve their utility in precision agriculture.

Off-grid power sources can generate or store a certain amount of energy; thus, they cannot power multiple devices or appliances simultaneously, thereby limiting their applicability in WSNs. The high initial cost of installing and maintaining off-grid power sources also makes them unaffordable. They are also unreliable sources and require specialized skills for maintenance and repair, which can be challenging for individuals without necessary expertise. However, they can enhance the scope of SMSS to regions that have yet to potentially benefit from WSNs. The current technological solution for powering IoT-based devices relies mainly on batteries. However, their lifetimes are generally much less than the expected lifetimes of the WSNs; hence, periodic replacement of batteries is required to keep the devices operational. This creates extra expenses and additional complications for remote sensors. Also, batteries are expensive, bulky, and contain harmful chemicals. Although efforts are currently being made to improve the energy storage capacity and, therefore, the lifetime of IoT devices, the miniaturization of batteries remains a major technological challenge. Various energy sources like solar and RF can be used as energy harvesters to charge a sensor's super capacitor, indicating an interest in sustainable and off-grid power sources. There are other off-grid ambient energy sources which can be used as energy sources such as microbial fuel cells (MFCs) (e.g. Soil MFC, Plant MFC, Sediment MFC and terrestrial MFC) in which bacteria's from soil generate electricity. Theoretically, sensor nodes powered by MFCs have eternal lifetimes.

Biodegradable sensors have been tested for their environmental biodegradability and corresponding effects on crop growth. However they have not been applied much in agricultural applications, and require substantial R&D support to enhance their capabilities. More research is needed to test the applicability of biodegradable sensors in soil moisture sensing, exploring their scope of applicability, accuracy (contextualized to their application), sensitivity to environmental factors (e.g., sensitivity to variations in temperature, salinity, and pH), and suitability across microbiome conditions (e.g., the effect of rhizosphere biological activity and organic matter in the soil zone). Studies to determine the scope of application would include investigations of the required accuracy, budget, qualified labor demand, sampling volume, and life expectancy. Furthermore, the sensor response time (to changes in the surrounding moisture conditions) is significantly longer in biodegradable sensors; this would require research to bring it to an acceptable limit useful for specific agricultural or other applications. To conclude, the challenges facing the design of truly biodegradable sensors include the fabrication of conductive biodegradable materials, wireless communication, power supply, power efficiency, quality of the substrate material and control of elimination rates.

Research and development in soil moisture sensing needs to be aligned towards specific applications and constrained by different contextual realities (e.g., costs, accessibility to the power grid, and environmental sustainability). Some applications may require soil moisture monitoring at finer observational scales of time or space (such as flood forecasting), while others may require observations at larger scales (such as drought monitoring). These would then influence relevant parameters for the design of the SMSS, such as sensor response time and whether a WSN is needed (and if yes, the spatial density of the sensors). Screening and pre-assessment of different components need to be tested individually and in combination with other biodegradable polymers. Experimental designs can be adapted from previous studies to test the accuracy of the sensors, develop appropriate calibration functions and quantify (and correct for) environmental sensitivity in laboratory conditions. Finally, field studies are required before full implementation of these solutions could be realized.

CRediT authorship contribution statement

Sumit Maya Moreshwar Meshram: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Soham Adla:** Writing – review & editing, Writing – original draft. **Ludovic Jourdin:** Writing – review & editing, Supervision. **Saket Pande:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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